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PHYSICAL AND MECHANICAL RELATIONSHIPS IN ELECTRO SLAG (ESR) STE--ETC(U)
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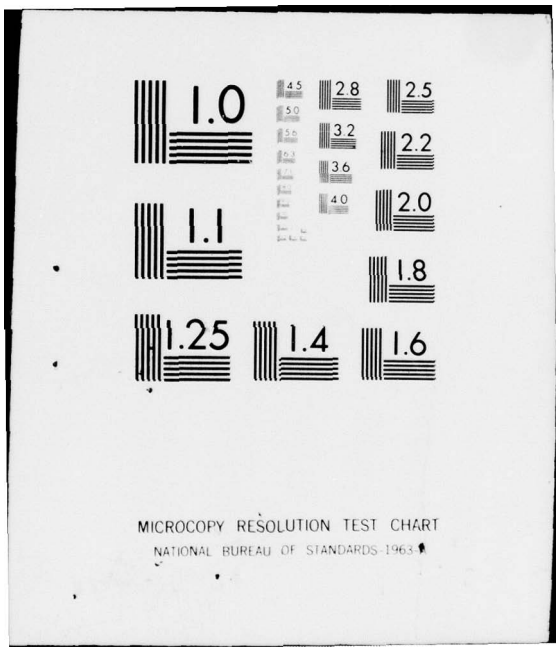
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PHYSICAL AND MECHANICAL RELATIONSHIPS IN ELECTRO SLAG (ESR) STEEL

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14 p.

Electroslag remelting of gun steel has been proposed as an alternate manufacturing process because of reported improvements in mechanical properties and potential economic benefits. These improvements are a result of the effective control of the many variables inherent in the process.

In order to obtain a uniform microstructure while avoiding piping, porosity and macrosegregation, a unidirectional solidification mode is desired(1). This mode of solidification, together with the relatively short holding times of the molten metal, also affects the distribution of second phase particles, for example, it results in a more uniform carbide distribution because the carbides are not allowed to grow in the transverse or longitudinal directions.

The slag layer plays many roles. The composition of the slag is a vital factor in determining the net composition of the final product. A slag that is too reactive removes desired alloy elements, while one that is not reactive enough results in inadequate cleanliness(2).

Another advantage of the slag is its presence between the mold and the solidified metal. This results in a smooth ingot surface requiring minimal finishing and conditioning. However, in order to avoid excess slag along the sides of the mold, the distance between the electrode tip and the molten metal pool should be kept at a constant value; the exact distance depending on the specific alloy being produced.

The amount of non-metallic inclusions can be controlled within certain limits with the slag layer(3). The non-metallic matter becomes dissolved in the slag, lowering the amount of inclusions in

the finished product and distributing those that do result more evenly. One of the most deleterious elements removed in this manner is sulfur[4],[5]. Desulfurization of the metal usually results in better mechanical properties and weldability than can be obtained with conventionally cast materials.

Controlling the hydrogen level in the ingot also enhances the weldability, ductility, fracture toughness and fatigue life of the alloy produced[6]. Vacuum degassing of the electrodes prior to melting reduces their hydrogen level thereby reducing the amount of hydrogen in the ingot[2].

High ingot yield is another reported advantage of the electroslag remelt process. It has been shown that the depth of the molten metal pool is critical in achieving this. The optimum condition is a shallow pool, which can be maintained by correct control of the power source. Preserving a constant electrode to molten metal pool distance is also an aid in attaining high yields.

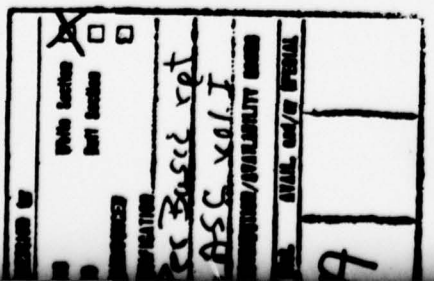
Electroslag remelting of other alloys is also possible because of the uniform microstructure that results. In experiments on Cr-Fe alloys, changing the ingot diameter from 60mm to 250mm and altering the Cr content had no affect on the uniformity of the microstructure[7].

Another procedure that can help in obtaining a uniform microstructure is constant agitation of the molten metal pool to ensure mixing of all the alloying elements. This can be affected by stirring of the pool or rotating the base plate of the apparatus. However, this is only supplemental to maintaining a uni-directional solidification mode in obtaining a uniform microstructure.

In the current study, it was decided that in order to evaluate the cited potential benefits of ESR material, several ingots of ESR melted 4335 + V should be obtained from various manufacturers to the same chemical requirement. It should be noted that at the time of the inception of this program, the primary emphasis of ESR melting was in the production of tool steels and superalloys with little going toward the production of alloy steel billet.

Procedure: ESR material corresponding to a nominal 4335 + V alloy steel was ordered from five (5) producers including one European producer. While it would obviously have been desirable to obtain the complete log of melt practice from the suppliers, such information could not be obtained since it was considered proprietary by the producers. However, some information was obtained and is shown in Table I.

The aim composition, together with the actual compositions, are shown in Table II. The original ingots were 12" diameter which were forged to 7-1/4" billets. In one case, a 10" diameter billet was obtained and forged to 7-1/4" diameter in order to evaluate the



effects of forging reduction.

The ingots were then sectioned and mechanical properties, chemical analysis, microprobe analysis obtained. The mechanical properties were derived from transverse bars heat treated as 1" square blanks, thereby effectively eliminating heat treatment variations as a possible cause of variations. Tensile tests were conducted at 72°F (21°C) while impact tests were conducted at -40°F (-40°C).

The material tested was tempered at varying temperatures. However, 975°F and 1125°F are the only tempering temperatures for which data was obtained for all five heats. Other tempering temperatures of 1000, 1050 and 1100°F were applied to selected heats, as shown in Table III.

The hardenability of the various heats was determined using the method proposed by Hollomon and Jaffee. This method, similar to others, uses hardenability factors for each element (Table IV) which are multiplied by the concentration of each element to determine the maximum diameter of an ideal round which can be hardened.

Microhardness tests were run on a Tukon Hardness Tester employing Knoop hardness. This was felt to be superior to Vicker Hardness Tests because of the greater sensitivity of the Knoop hardness to microstructural changes. One hundred random readings were obtained on polished specimens from each heat tempered at 975°F.

Optical metallography was performed on samples from each heat tempered at 975°F in order to observe the microstructure and the dendrite arm spacing.

A microprobe analysis for Cr, Ni, and Mn was done on samples tempered at 975°F from each manufacturer. The method used in this analysis was to perform a continual scan on the specimen over a specific region. The total number of counts for a fixed time period was determined for each element of interest. This count was then corrected for background level and expressed as total counts as a function of distance in microns. In this way, compositions as a function of position could be determined. The specimens were oriented so that the scan would be perpendicular to the axis of the dendrites.

Discussion and Results:

a. Chemical Analysis - The results and the general chemical analysis are shown in Table II. As can be seen, most of the chemical compositions are within the aim chemistry with a few minor variations. However, there are two factors which should be discussed regarding chemical composition. The first is that even though the chemical compositions are within the aim, a range of compositions does exist and this variation has the capability to affect the mechanical

properties. For this reason, a hardenability calculation was made on the actual compositions derived for the various heats. As can be seen from an examination of the data presented in Tables II and IV, there does exist a range of hardenability with the C material exhibiting the greatest hardenability and the D material the least. The ramifications of this variation will be discussed somewhat more fully in a later section.

A second factor involving chemical analysis which should be discussed is the distribution of the compositional elements. In many respects, it is the distribution of the elements, rather than the nominal composition, which controls mechanical properties. For this reason, a microprobe analysis was also conducted on the material as previously described.

d. Microprobe Analysis - The results of the microprobe study for the 5 heats (3 elements) were also examined. These data illustrate the distribution of a particular element in a linear scan over the surface. It was obvious from our examination of the data that some of the heats were more uniform in concentration and displayed less periodicity than do others. For example, in examining the traces of concentration vs distance, the distinct presence of a periodic distribution was quite evident in Heat C.

In order to determine the variation in uniformity of the microprobe data, a statistical evaluation was undertaken using the following technique.

The numerical value of the concentration (counts) was determined at each 10 μ interval in distance. The data was then analyzed statistically to determine the mean concentration (expresses as counts) and the standard deviation and variance from that mean. The data are shown in Table V. The D heat was considerably more uniform than any of the others whereas the C heat showed the greatest variation in concentration exhibiting the greatest variance in all three elements.

c. Hardenability - The hardenability of each heat, expressed as the diameter of an ideal round (D_I) is shown in Table II. The values range from 14.459 inches for Heat C to a low of 13.334 inches for Heat D. It is interesting to note that the low hardenability resulted not from a lack of any single element, but rather from the fact that all elements were on the low side of the compositional range. The significance of the hardenability as a factor in determining the obtained properties will be discussed in a later section, (Mechanical Properties).

d. Microhardness - The microhardness data has been summarized and statistically analyzed. The summary of these data are presented in Table VI. The data shows that the D heat exhibits the

least variation in the microhardness, a fact which is consistent with the results observed in the microprobe testing. This, however, was the only heat where a correspondence was observed. In general, the microhardness variance data did not correlate well with the ranking of the heats on the basis of microprobe tests. However, when one examines the mean microhardness level, one finds that the resultant microhardness level is affected both by the alloy level in the heat (hardenability) and by the microdistribution of these elements. For example, if one projects the expected microhardness for each heat on the basis of the calculated hardenability, it would be expected that the C heat would exhibit the highest mean value, whereas in fact, it is ranked lower. Conversely, it would be expected that the D heat would exhibit the lowest mean microhardness on the basis of its calculated hardenability. In reality, the mean microhardness is higher than expected. The significance of the finding is simply that a higher hardenability can compensate for larger dendrite spacing which might occur in melting due to poor control over melt or cooling rates.

Mechanical Properties: The mechanical properties of the 5 heats after forging and tempering at 975°F are shown in Table III. Examination of the data also shows that while there is not a significant variation in the yield strength and tensile strength, there are large variations in the ductility parameters (Heat E being the poorest) and in impact strength. The data also shows the Heats A and B at the top based upon both their impact strength and ductility. This is consistent with their generally high ranking in hardenability, dendrite spacing and microprobe distribution.

Heat E displayed the poorest overall performance exhibiting not only the lowest ductility, but low impact values as well. Because of the abnormal behavior of this heat relative to the expected ductility for this grade material, it was subjected to gas analysis. This gas analysis revealed that the oxygen content was approximately 198 ppm, thereby accounting, in part, for the low ductility and impact strength.

After tempering at 1125°F, Heats A and B are still ranked at the top of order with respect to impact strength and ductility; however, the yield strength level is somewhat lower than Heat C.

Also, Heats C and D have reversed the ranking from the 975°F temper with Heat D now exhibiting superior impact strength at the 1125°F temper.

Summary and Conclusions: A review of the various properties obtained on the 5 heats (summarized in Table VII) reveals that a wide variation of mechanical properties, more specifically the ductility and impact values, is possible even though all heats are within the specified chemistry range and are melted utilizing acceptable melt practices and procedures.

The variables which appear to affect the properties most profoundly are the hardenability and the dendrite arm spacing which presumably is related to the rate of melting.

The mean microhardness level was related both to the hardenability for a particular heat and the microprobe distribution of the elements, a heat with good hardenability being adversely affected by an uneven distribution of the alloying elements, the latter in turn, being affected by the melt rate for the heat. The significance of this information is that a higher hardenability would be expected to permit a wider variation in the melt rate without adversely affecting the mechanical properties. In summary, all the heats, with the exception of Heat E, were within acceptable limits for the alloy under study. Two of the heats, A and B, showed exceptional properties and undoubtedly represent the potential of the process for making high quality, high strength alloy steel economically.

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TABLE I
MELTING PARAMETERS

HEAT	A	B	C	D	E
Mold Dia.	12"	10"	12"	12"	12"
Current Type	AC	AC	AC	AC	AC
Flux Type	CaF_2-60%	CaF_2-60%	NA	CaF_2-60%	CaF_2-70%
	CaO-12	CaO-12	NA	CaO-10	
	Al_2O_3-28	Al_2O_3-28	NA	Al_2O_3-30	Al_2O_3-30
Flux wt. (lbs)	55.5	40	NA		52
Mold Material	Copper	Copper	Copper	Copper	Steel
Current, Avg.(amp)	7180	6300	NA	6000	9200
Voltage, Avg(volt)	44	47	NA	52	32
Melt Time (min)	136	110	NA	240	172
Ingot Weight (lb)	1130	960	3200	3415	1250

NOTE: NA - Not Available

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TABLE II

CHEMICAL ANALYSIS

ALLOY	C	Mn	P	Ni	S
Aim	.30-.35	.38-.50	.010 max	2.10-2.35	.010 max
A	.32	.52*	.009	2.28	.003
B	.33	.49	.009	2.25	.003
C	.30	.60*	.009	2.30	.003
D	.30	.40	.006	2.08	.004
E	.35	.45	.013	2.31	.010

ALLOY	Si	Cr	Mo	V	**Hardenability Ideal Round Diameter (in)
Aim	.25 max	.88-1.12	.45-.55	.06-.12	
A	.21	1.08	.49	.10	14.035
B	.17	1.05	.48	.10	13.708
C	.13	1.02	.60*	.10	14.449
D	.13	1.14*	.48	.07	13.334
E	.18	1.13*	.52	.07	13.684

*Outside specified range

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TABLE III
SUMMARY OF MECHANICAL PROPERTIES
(Tempered at 975°F)

PRODUCER	.1% YS (PSI)	UTS (PSI)	EL (%)	RA (%)	CHARPY (-40°F) (Ft-lbs)
A	172,850	191,250	18.1	55.2	27.4
B	173,500	189,675	16.1	50.8	24.9
C	170,500	192,000	15.7	50.4	14.0
D	169,800	186,800	15.7	49.6	12.0
E	175,025	191,550	9.3	24.6	14.0
		(Tempered at 1000°F)			
C	169,000	192,300	16.8	54.4	14.2
D	167,600	186,800	14.7	40.4	18.5
		(Tempered at 1050°F)			
C	164,700	187,300	15.7	49.6	14.7
D	164,600	182,800	16.8	54.2	23.6
		(Tempered at 1100°F)			
C	159,300	183,200	17.1	55.8	17.5
D	157,700	172,900	14.3	42.0	41.7
		(Tempered at 1125°F)			
A	151,056	164,045	19.3	60.9	59.3
B	150,752	162,476	18.3	57.9	48.1
E	149,548	157,463	6.1	11.4	23.8
C	157,500	181,200	19.1	57.5	19.5
D	156,100	170,900	17.1	43.5	43.1

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TABLE IV - EFFECT OF CARBON AND ALLOYING ELEMENTS ON HARDENABILITY* (IDEAL ROUND)

Element		Pearlitic Hardenability Factor	Bainitic Hardenability Factor
Carbon	(50% pearlite or bainite	0.338 x % C in./	0.494 x % C in.
	(almost no pearlite or bainite)	0.254 x % C in./	0.272 x % C in.
Manganese		1 + 4.10 x % Mn	1 + 4.10 x % Mn
Phosphorus		1 + 2.83 x % P	1 + 2.83 x % P
Sulfur		1 - 0.62 x % S	1 - 0.62 x % S
Silicon		1 + 0.64 x % Si	1 + 0.64 x % Si
Chromium		1 + 2.33 x % Cr	1 + 1.16 x % Cr
Nickel		1 + 0.52 x % Ni	1 + 0.52 x % Ni
Molybdenum		1 + 3.14 x % Mo	1
Copper		1 + 0.27 x % Cu	1 + 0.27 x % Cu

*After Hollomon and Jaffe (277)

/ For grain size A.S.T.M. 7

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TABLE V
STATISTICAL EVALUATION OF MICROPROBE DATA

Heat No.	A	B	COUNTS C	D	E
Mean					
Ni	917.50	848.33	749.44	974.09	860.67
Mn	867.41	403.89	622.78	417.27	303.33
Mo	400.00	300.69	155.00	115.00	121.33
Standard Deviation					
Ni	47.73	53.50	97.19	45.95	59.55
Mn	29.45	32.29	120.86	36.49	57.90
Mo	20.00	17.34	53.68	9.49	36.86
Variance					
Ni	2278.57	2862.50	9446.52	2114.09	3545.95
Mn	867.41	1042.36	14606.95	1331.82	3352.38
Mo	400.00	300.69	2881.25	90.00	1358.81

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TABLE VI

SUMMARY OF MICROHARDNESS DATA

HEAT	MEAN	MEDIAN	STANDARD DEVIATION	MODE	VARIANCE
A	522	504	20	509	400
B	494	465	19	475	361
C	505	504	18	498	324
D	521	480	10	480	100
E	459	434	16	438	256

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TABLE VII

RANKING OF HEATS BY VARIOUS ATTRIBUTES

TEMPERED AT 975°F

	1st	2nd	3rd	4th	5th
UTS	C	E	A	B	D
.1% Y.S.	E	B	A	C	D
%El	A	B	C/D		E
%RA	A	B	C	D	E
Impact	A	B	C/E		D
Dendrite Spacing	D	A	B	C	E
Microhardness Mean	A	C	D	B	E
Standard Deviation	D	E	C	B	A
Hardenability	C	A	B	E	D
Microprobe	D	A	B	E	C